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CONTINUOUS EXPLOSIVE FRAGMENTATION TECHNIQUES

Richard W. Watson, et al

Bureau of Mines

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Research has been conducted relating to the optimization of explosives and initiation systems for a proposed automatic continuous drill-and-blast tunneling system. Experiments concentrated on the development, characterization and selection of explosives which could be automatically

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20. ABSTRACT (Continued)

injected in bulk form into a borehole and which have optimized safety, initiation, energy and economic characteristics, and the development of reliable, economical, remote initiation systems. The experiments demonstrated that a variety of explosive systems exist whose detailed formulations can be tailored to minimize toxic fumes, optimize safety and initiation characteristics. These systems can be made compatible with bulk injection and proposed methods of remote initiation and are capable of high energy at reasonable cost. Projectile impact was shown to be a reliable, simple and economical technique for remote initiation. Laser initiation of fuse caps may be another possibility for remote initiation.

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CONTENTS

ILLUSTRATIONS

TABLES

CONTINUOUS EXPLOSIVE FRAGMENTATION TECHNIQUES

1. Technical Report Summary

The research described below was directed toward a specific application of explosives to underground blasting. The concept involves excavating tunnels using an automated quasi-continuous drill-and-blast technique. The proposed technique is based on the development of a single machine incorporating borehole drilling equipment, explosive mixing and injection apparatus, an integral system for initiating the explosives, and equipment for muck removal. The entire process is planned to be automated so that drilling, explosive injection and muck removal could proceed simultaneously and essentially continuously except for momentary interruption to fire a charge. This research program was directly concerned only with those aspects of the total concept which directly bear on the explosive used, and was broken down into two phases: the development/selection of the explosive, and the development/selection of a suitable remote initiation system.

Detailed characterization studies were performed on a variety of commercial explosives and previously developed experimental explosives, with special attention to suitability for on-site mixing, bulk injection, sensitivity, initiation characteristics, energy output and toxic fume production. In addition, a development effort was specifically aimed toward further optimization of the explosives to the application proposed. There is, of course, no "ideal" explosive but a variety of formulations were found that can be recommended for the purpose.

Development of the initiation system was particularly important

since, on the one hand, the hookup of conventional electric blasting caps and detonating cord by automated machinery would greatly complicate the operation and, on the other hand, the conceptual blasting patterns and schedules involve essentially independent initiation of short boreholes so that the cost per cubic yard attributable to the initiator can be high unless special attention is given to minimizing the cost per shot.

The use of initiating devices such as electrical, fuse-type or mechanically initiated ("stab") blasting caps, while certainly feasible, is costly, and research was therefore concentrated on the feasibility of directly initiating the explosive by injection of radiation, flame, reactive chemicals or projectiles. The conclusion drawn is that projectile impact affords the simplest, most economical technique for remote initiation.

2. Introduction and Background

The need for improvements in the speed and economics of underground excavation is widely recognized and is relevant to a variety of national needs including transportation, defense and mineral and energy resource development (15, 19).[1/] Accordingly, the U. S. Department of Defense has sought to advance tunneling technology through the Advanced Research Projects Agency (ARPA) program for Rock Mechanics and Rapid Excavation. The work reported herein represents one aspect of that portion of the program which was conducted by the Bureau of Mines, specifically the application of conventional explosives to advanced

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1/ Underlined numbers in parentheses refer to items in the list of references at the end of this report.

excavation technology.

A variety of methods of removing rock have been conceived and proposed which may be roughly divided into thermal and mechanical techniques. Thermal techniques usually involve the melting of a substantial portion of the rock to be removed, although some proposed techniques involve disruption by thermal shock or gaseous decomposition products and may be more properly called thermo-mechanical. The mechanism of heat input may be electromagnetic (e.g., laser or radio frequency) radiation, electron beams, hot gas jets (e.g., torch flames), etc. All thermal methods have a very low efficiency in energy expended per volume of material removed, viz., of the order of magnitude 10^3 joules per cubic centimeter or greater. Mechanical methods usually involve the application to the surface of the rock of sufficient force to overcome the tensile or shear strength by impact (e.g., percussive drilling), mechanical cutting or blasting techniques. Such techniques are capable of very good efficiency relative to thermal methods, although the numerical range is great, ranging from a few tens of joules/cc to several hundred joules/cc, unless they are applied near an existing free surface when values less than 1 joule/cc are possible. The particular advantage of explosive (drill-and-blast) techniques is that the emplacement of the energy source within the rock (behind the free surface) enables the energy to be applied as tensile stress against the free surface with correspondingly great efficiency, of the order of a few joules/cc.

The study described in this report was conceived with the intent

of optimizing the efficiency of tunnel-driving operations using the drill-and-blast cycle by (1) taking advantage of improved blasting patterns and (2) adapting to automated, quasi-continuous operation within the context of the concept to be described in the following section.

3. Concept

The fundamental conceptual framework of the research described herein was developed by Rapidex, Inc., under a separate contract also funded by the ARPA Rock Mechanics and Rapid Excavation program, and is described in a separate report (16). However, the general features are described here for the convenience of the reader.

The key to efficient use of explosives or, for that matter, any mechanical technique of rock removal is, as already stated, the application of energy against a free surface. In conventional drill-and-blast tunneling operations, this is done by angling the boreholes near the center of the face toward the tunnel axis (or a median plane), circumscribing a conical, pyramidal or wedge-shaped mass of rock which is blown out first, producing a "cut"; the charges surrounding this cut are then fired a few milliseconds later and are able to take advantage of the presence of two free surfaces, i.e., the face itself and the surface of the cut; the cut is thereby enlarged and the charges in the next ring around the enlarged cut are fired etc., until the periphery of the tunnel is reached.

There are other possible variations of this technique, but for the most part two disadvantages remain: (1) the whole face is blasted at

once, producing an enormous amount of rock fragments (muck) which must be removed before further drilling can commence; and (2) each blasting cycle leaves a new face which is without any major secondary free surfaces indenting it; these must be created anew each blast cycle.

These disadvantages are largely avoided by a blasting pattern which removes only part of the face during each cycle and which exposes a new face which already is indented by a secondary free surface. Such a pattern is the spiral blasting concept. In this concept, the face (which need not be circular, though it is more easily visualized as circular) is not flat or uniformly concave; rather, it is intersected by a surface, in effect a bench face, which is oriented radially when viewed along the tunnel axis and which is parallel to the tunnel axis. The remainder of the face deepens progressively with increasing azimuthal angle from the top of this bench until it intersects the bench again at its foot. This surface is easily described neither verbally or graphically but may be visualized by looking at the front end of an auger or a twist drill, bearing in mind that these devices are normally <u>double</u> spiral. This pattern has the double advantage that (1) charges may be placed behind the radial free face so as to gain the advantage of working on a free face and at the same time by blasting out a wedge-shaped volume of rock, create a new free face identical to the original except that it is shifted azimuthally (rotated) with respect to it; and (2) since only a fraction of the face is blasted at one time, conceivably the muck pile would be small enough that the drilling equipment could be moved up to the face so that drilling and muck removal could go on simul-

taneously. The embodiment of the concept would be a single machine which could combine all of the operations of the drill-and-blast cycle, viz., drilling, explosive placement, explosive initiation and muck removal. The system would excavate a tunnel by blasting our skewed pie-shaped sections in a spiral pattern. One of the significant features of the concept is that with proper components the system would be capable of a high degree of, or even total, automation.

However, several problems must be overcome to make such a concept practical. Because this study was restricted to the adaptation of chemical high explosives to the spiral drill-blast concept, some of these details do not concern us here; those problems which directly involve the explosive may be broken down into two categories: (1) explosive characteristics and optimization, and (2) initiation methods and development. These problems will be described in the following sections.

4. Explosives Characterization

The effective use of chemical explosives or blasting agents[2/] in a system of the type proposed requires the optimization of a number of characteristics which may be grouped under the headings of effectiveness and safety. To be effective the explosive must be capable of being initiated conveniently, must detonate reliably in boreholes of the diameter intended, must have a shattering and heaving effect (energy) commensurate with the strength of the rock to be blasted, and should be inexpensive. In addition, for the type of application considered here, the explosive must be suitable for bulk loading into horizontal holes, i.e., a semi-

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2/ In essence, a blasting agent is a substance which cannot be detonated by a No. 8 blasting cap under light confinement but can be detonated under proper loading conditions.

rigid paste or gel. To be safe, the explosive should be insensitive to initiation by spurious stimuli such as impact, shock, friction, flame, etc., should produce a minimum of toxic fumes when detonated, and ideally, for the application envisioned, should be capable of being mixed at the loading site from inert ingredients. The following paragraphs describe the tests which were used in this program to screen, characterize, and evaluate a selection of explosives considered potentially useful in the proposed application. The candidate explosives included conventional nitroglycerin dynamites, commercial water-base gel explosives, experimental water-base and nitroparaffin-base gel and slurry explosives, and commercial two-component (mix-in-situ) explosives. The tests employed are described by Mason and Aiken (14) in detail, and are described briefly here for the convenience of the reader.

4.1 Cap Sensitivity Test

The cap sensitivity test provides the simplest index of the sensitivity of an explosive substance and essentially discriminates between "explosives" and "blasting agents". A sample of the explosive is poured into a 1-qt cylindrical cardboard container (quantity sufficient to fill to a depth of at least 4 inches), a No. 8 electric blasting cap is inserted and fired. Detonation of the sample (as indicated by cratering of the ground, concussion, etc., with complete consumption of the sample) indicates that the sample is cap-sensitive and to be classified as an explosive. Explosive substances which do not detonate in this test are classed as blasting agents. The latter require boosters for initiation and are usually usable or economical only in large-diameter holes

and are not considered practical for the application under discussion.

4.2 Projectile Impact Sensitivity Test

The projectile impact sensitivity test as used by the Bureau is adapted from that originally described by Eldh (8). The projectile launcher is a modified 1918 .50-caliber Mauser bolt action anti-tank gun, refitted with a .50-inch smooth-bore barrel. The projectiles are .50-inch diameter, .50-inch-long brass cylinders with a slight chamfer at the rear; the cartridge case is standard .50-caliber machine-gun ammunition. The muzzle velocity is controlled by the type and quantity of propellant loading. The overall setup is sketched in fig. 1. The projectile velocity is measured by determining the time of flight between two electrically conductive tapes (such as are used for sensing end-of-reel on magnetic tape reels) spaced 50 cm apart. Breaking the first and second tapes respectively starts and stops an electronic counter-chronograph capable of 0.1 microsecond resolution.

The explosive sample is located 10 feet from the muzzle and is normally confined in a 1-1/2 by 3-inch Schedule 40 steel pipe nipple sealed with 3-mil polyethylene sheet at each end; a "witness plate" (4 by 4 by 1/4-inch mild steel plate) may be used immediately behind the charge to verify detonation in ambiguous cases--a hole punched in the witness plate indicates detonation of the charge. A stub of detonating cord inserted in the rear end of the acceptor can also be used for the same purpose--detonation of the cord indicates detonation of the charge. However, unambiguous results are normally indicated by the survival or destruction of the confining pipe nipple (occasionally "partial reactions" are observed in which the pipe nipple is found warm and bulged or split).

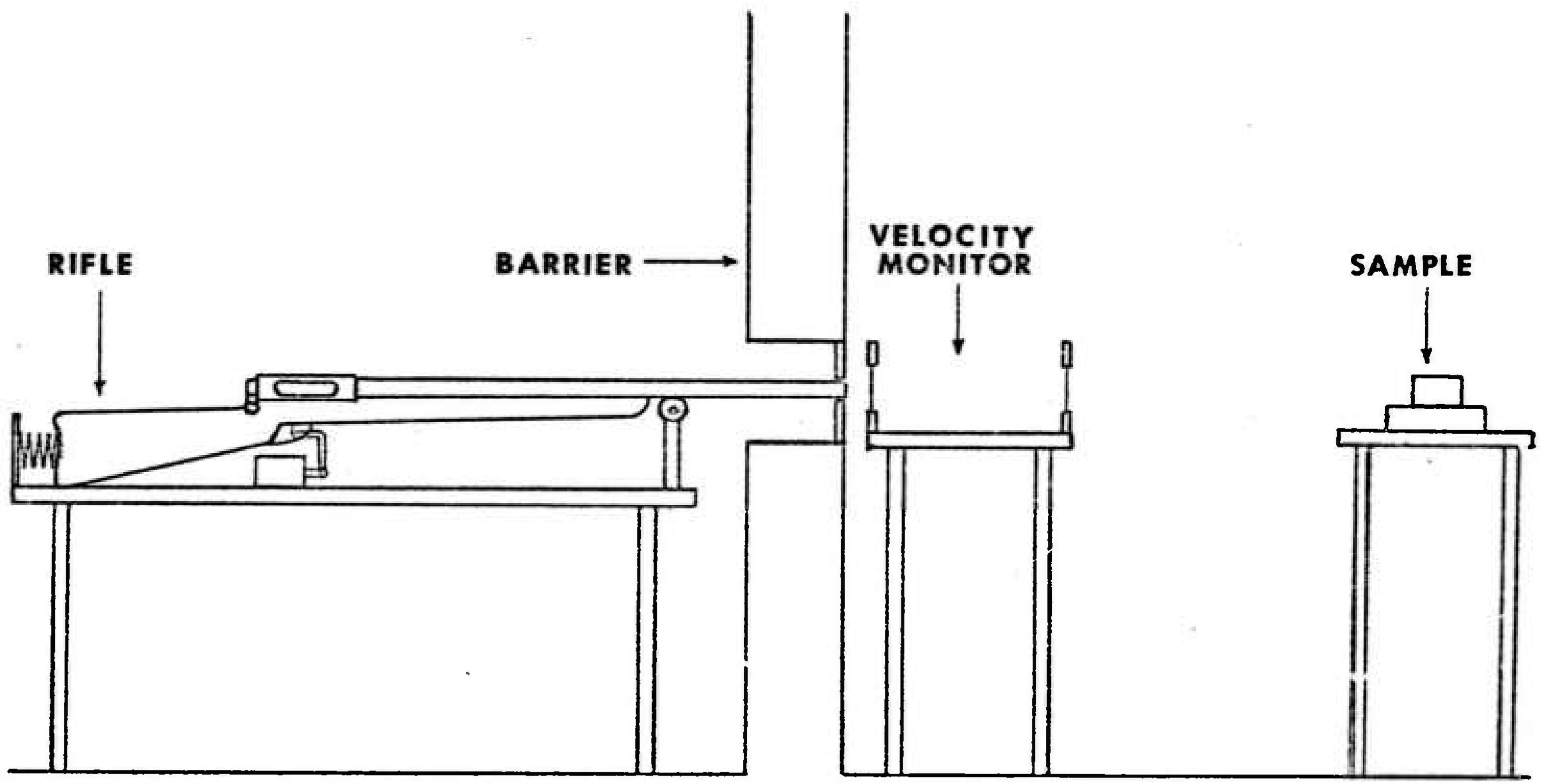

FIGURE 1. - Pictorial of projectile impact sensitivity test.

The results of this test, which consist of a set of positive or negative results as a function of projectile velocity, may be analyzed by the up-and-down technique (6, 5) to yield V_{50}, the projectile velocity corresponding to a 50 percent probability of initiating the sample; however, if there are no reversals (one or more positive results at lower velocity than one or more negative results), which is usually the case with this test unless the physical properties (density, homogeneity) of the sample are poorly controlled or unless very small increments are taken, it is usually sufficient to take V_{50} as the mean between the highest velocity at which negative results are obtained and the lowest velocity at which positive results are obtained.

The precision of this test is very good and the results correlate very well with cap sensitivity (materials with a V_{50} of less than 750 m/sec are generally cap-sensitive and those with V_{50} greater than 850 m/sec are generally not cap-sensitive). The results also correlate well with those of the card-gap test at least for explosives of small critical diameter. Because of the importance attached to projectile impact as a potential method for remote initiation, as discussed in later sections, primary emphasis was given to this sensitivity test.

4.3 Detonation Velocity Measurement

Interest in the velocity of detonation of an explosive stems primarily from the correlation of detonation velocity with "brisance" or shattering power, even though this correlation is not unique. Also, measurement of the detonation velocity, particularly a continuous measurement as described below, can give important information on the sta-

bility of detonation and charge diameter effects.

Detonation velocity can be conveniently measured in one of three ways. One of these is the D'Autriche method: the ends of a loop of detonating cord, whose detonation velocity is known, are inserted, a known distance apart, into a cartridge of the explosive being tested; the detonation waves initiated in the cord will collide at a point (marked by laying the cord against a lead plate) whose distance from the center of the loop is proportional to the transit time of the detonation in the cartridge between the two ends of the detonating cord.

A similar method, using electronic instrumentation, measures the transit time of the detonation between two sensing "switches" (each of which may simply be a pair of enameled wires twisted together) inserted a known distance apart in the cartridge, using an electronic counter-chronograph.

A greatly superior method, however, is the continuous velocity probe (10); this yields a record of the detonation velocity at each point along the charge and is very useful in revealing buildups or decay of detonation, transitions between low- and high-velocity detonation or the reverse, and other forms of instability. The sensing element is the probe itself, one form of which is shown in fig. 2. The probe consists of a core of fine bare resistance wire, resistance typically a few ohms per cm, surrounded by a soft metal conducting sheath (fine aluminum tubing) with an insulating spacer in between; the latter can be a "skip-wound" nylon filament or a fine enameled wire. The probe is inserted longitudinally in the charge; the center conductor and the outer sheath are crimped

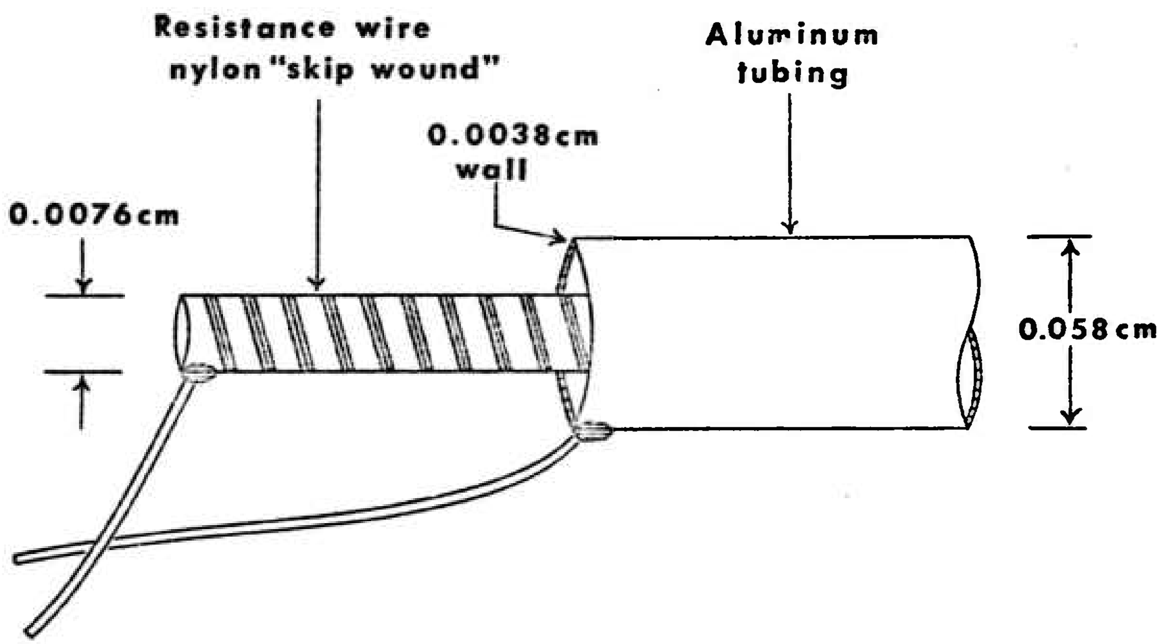

FIGURE 2. - Pictorial of velocity probe.

together at the end from which detonation is initiated. At the opposite end, the center and outer (grounded) conductor are connected to the constant-current generating circuit shown in fig. 3. The probe, whose inner and outer conductors are shorted together by the detonation front as it moves along, functions as a slide-wire rheostat whose resistance is proportional to the position of the detonation front. Since the current through the probe is held constant, the voltage across it is in turn proportional to the resistance and may be recorded oscillographically as a function of time.

4.4 Expanding Cylinder Energy Test

One of the most important parameters of an explosive is its available energy, i.e., the capacity to shatter and heave rock. There are a large number of tests and calculations purporting to determine the "energy" of an explosive, but since an explosive is called upon to do different tasks (e.g., rock shattering takes place at high pressure on a short-time scale and the heaving effect takes place over a much longer time scale at lower pressures) and since the tests employ different measures of performance, it is not surprising that no single test is uniquely useful nor that the various energy tests do not all correlate well one with another. One of the most sophisticated tests for determining the work done by an explosive at close range is the expanding cylinder test which is based on a research technique developed by Kury (12). The experimental arrangement is shown in fig. 4. The explosive is contained in a 1.0-inch i.d., 0.1-inch-wall copper cylinder initiated by a tetryl booster at one end. The detonation velocity is measured by a continuous

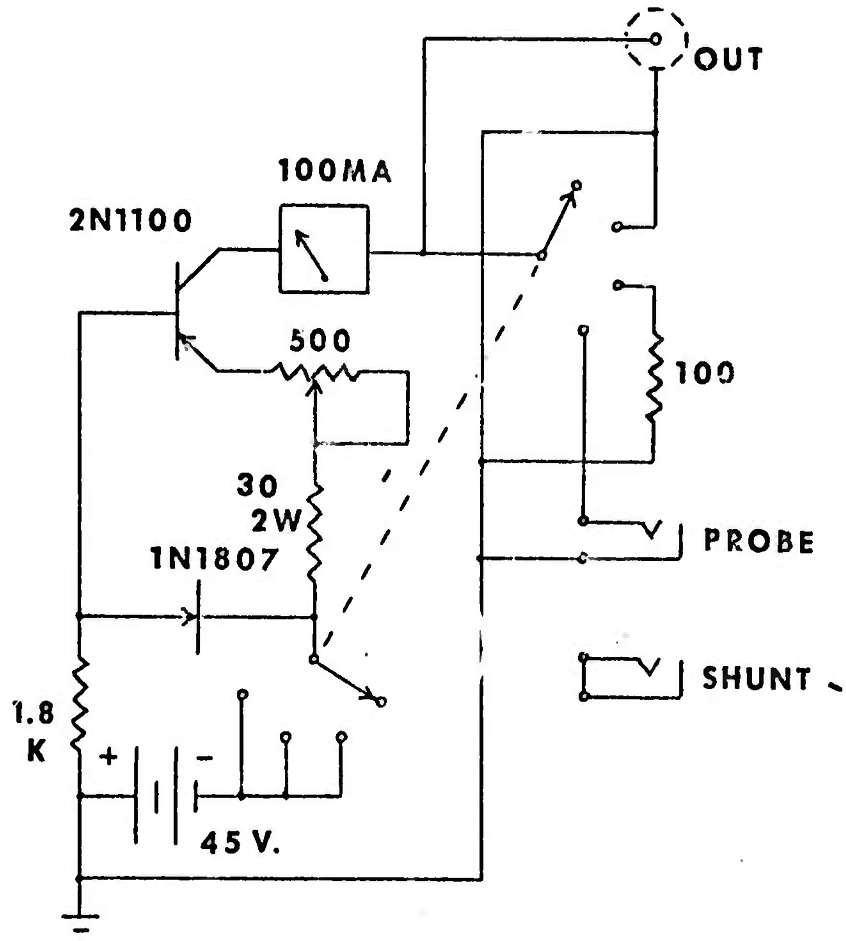

FIGURE 3. - Schematic of constant-current generator.

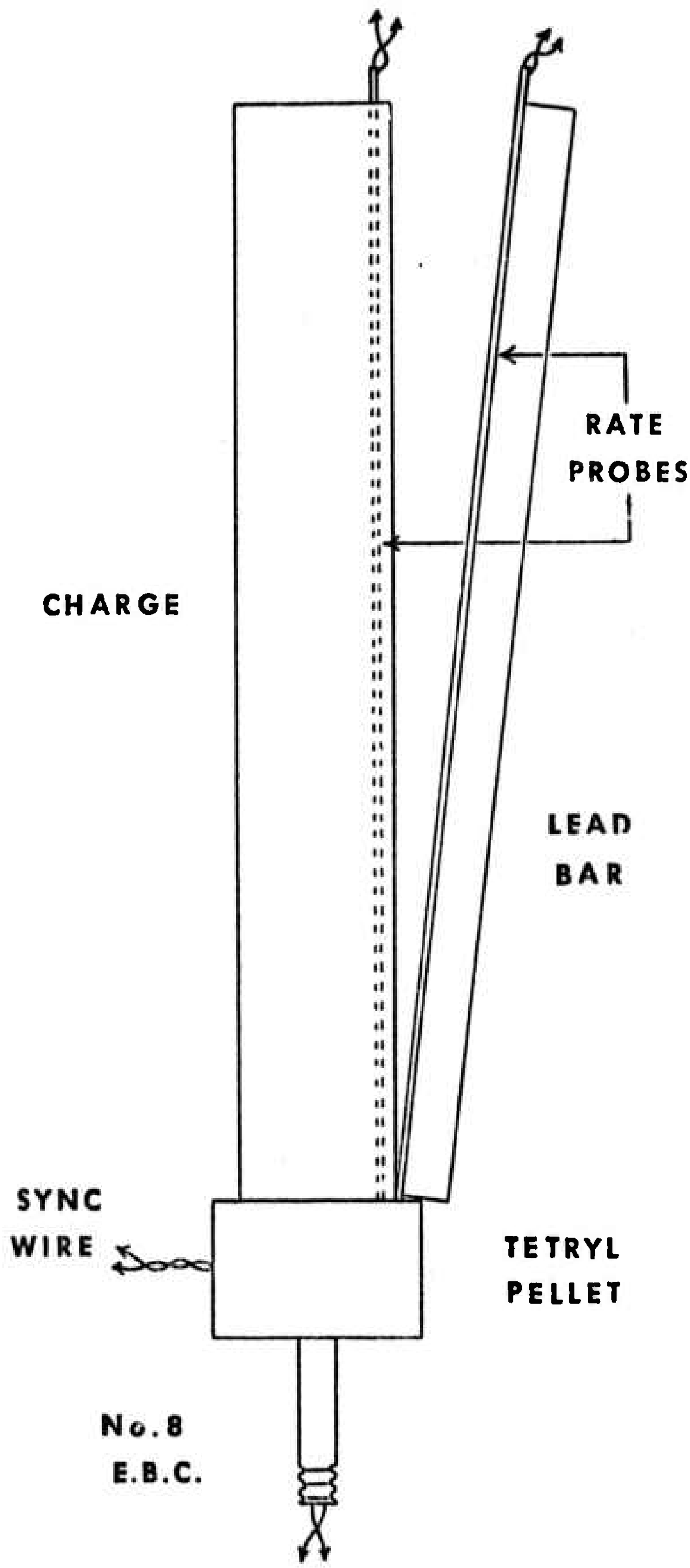

FIGURE 4. - Pictorial of expanding cylinder test.

rate probe in the charge as previously described. The expansion velocity of the wall is measured by a second probe external to the wall and slanted with respect to it; this probe is backed up by a lead bar to ensure that it is crushed by the expanding wall. From the measurement of the detonation velocity D and the slant velocity S, the radial wall velocity W can be calculated by

$$W = \frac{DS\ \sin\theta}{D-S\ \cos\theta} \tag{1}$$

where θ is the angle between the probe and the cylinder wall (initially). Assuming that the density of the detonation products varies negligibly with distance from the axis, that the radial velocity component varies linearly with the distance from the axis (out to the wall) and that the radial variation in the wall velocity is negligible, the radial component of the kinetic energy of the system is given by

$$E = 1/2\ (M_w/M_e + 1/2)\ W^2 \tag{2}$$

where M_w is the mass of the wall material and M_e the mass of the explosive. The "absolute" energy of the system as given above is converted to relative values by dividing by the value for TNT.

4.5 Underwater Test

One of the most useful energy determinations, in that it gives essentially two complementary measures of the explosive energy, is the underwater test (14, 3, 4, 9, 17, 11). This test is used at the Bureau of Mines Bruceton Station and is described in detail (14, 4); the layout is sketched in fig. 5. The explosive (950 grams) is contained in a 1-qt cylindrical cardboard container with a 2-inch diameter, 1-inch thick (80 gram) tetryl booster attached to one end which, in turn, is initiated by

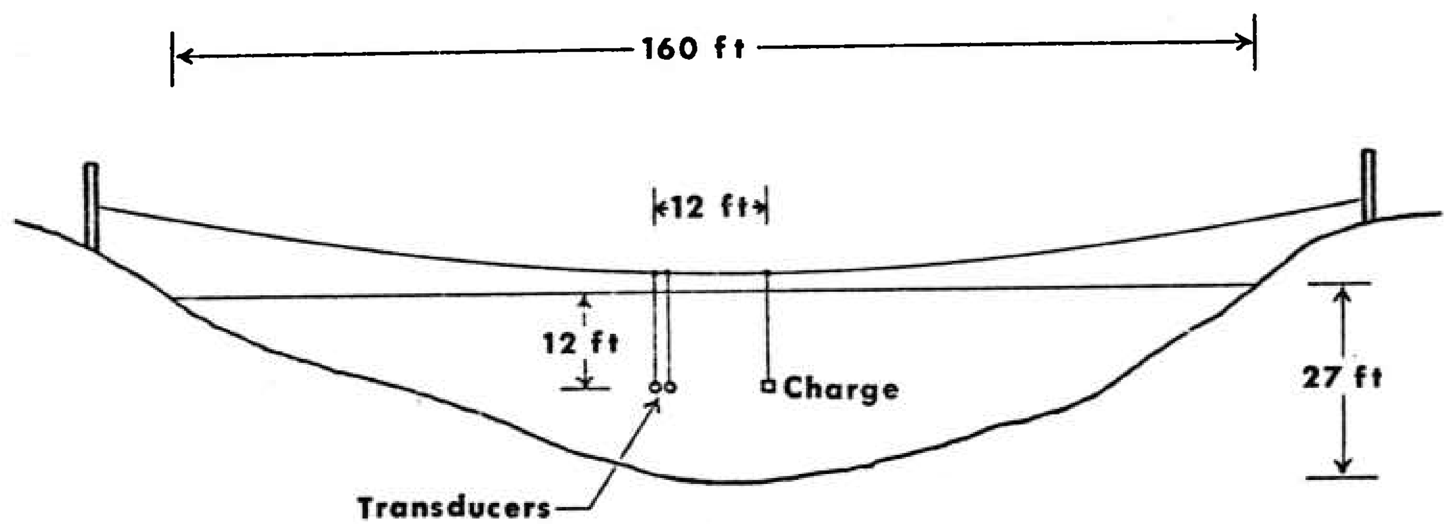

FIGURE 5. - Layout of underwater facility.

a 1-inch diameter, 1-inch long (10 gram) tetryl booster containing an electric blasting cap. If the explosive is not compatible with water, this assembly is wrapped in a polyethylene boot. The charge is suspended at a depth of 12 feet. Also suspended at a depth of 12 feet, and 12 feet away from the charge, are two piezoelectric transducers (one, 6 inches closer to the charge to provide a triggering signal for the electronics). The signals from these transducers are fed into the circuitry shown in block form in fig. 6. This circuitry performs two functions. The waveforms of the shock pulse is recorded oscillographically and the period of oscillation of the gas bubble is recorded digitally with high precision. The oscillogram of the transducer signal--voltage (pressure) vs time-- is digitized manually in 20-microsecond increments; the resulting values are then squared and integrated numerically, out to 400 microseconds, at which point further contributions to the integral are negligible. Since the velocity of the shock wave in the water does not vary much with peak pressure at the pressures involved, and since the peak pressures do not vary much from one explosive to another, the measurement of pressure vs time is equivalent to a measurement of pressure vs radius of the expanding spherical shock wave; and since the measurements are made at a constant radius, the integral of the pressure squared over the radius is equivalent to the integral of the pressure squared over the volume, which is proportional to the compressional energy contained in the shock wave ("shock energy") if the variation of compressibility with pressure is considered unimportant. The bubble oscillation period is directly related to the radius of the bubble at which the internal pressure crosses over the ambient pressure. Thus, the energy contained in the gas in the bubble ("bubble energy"),

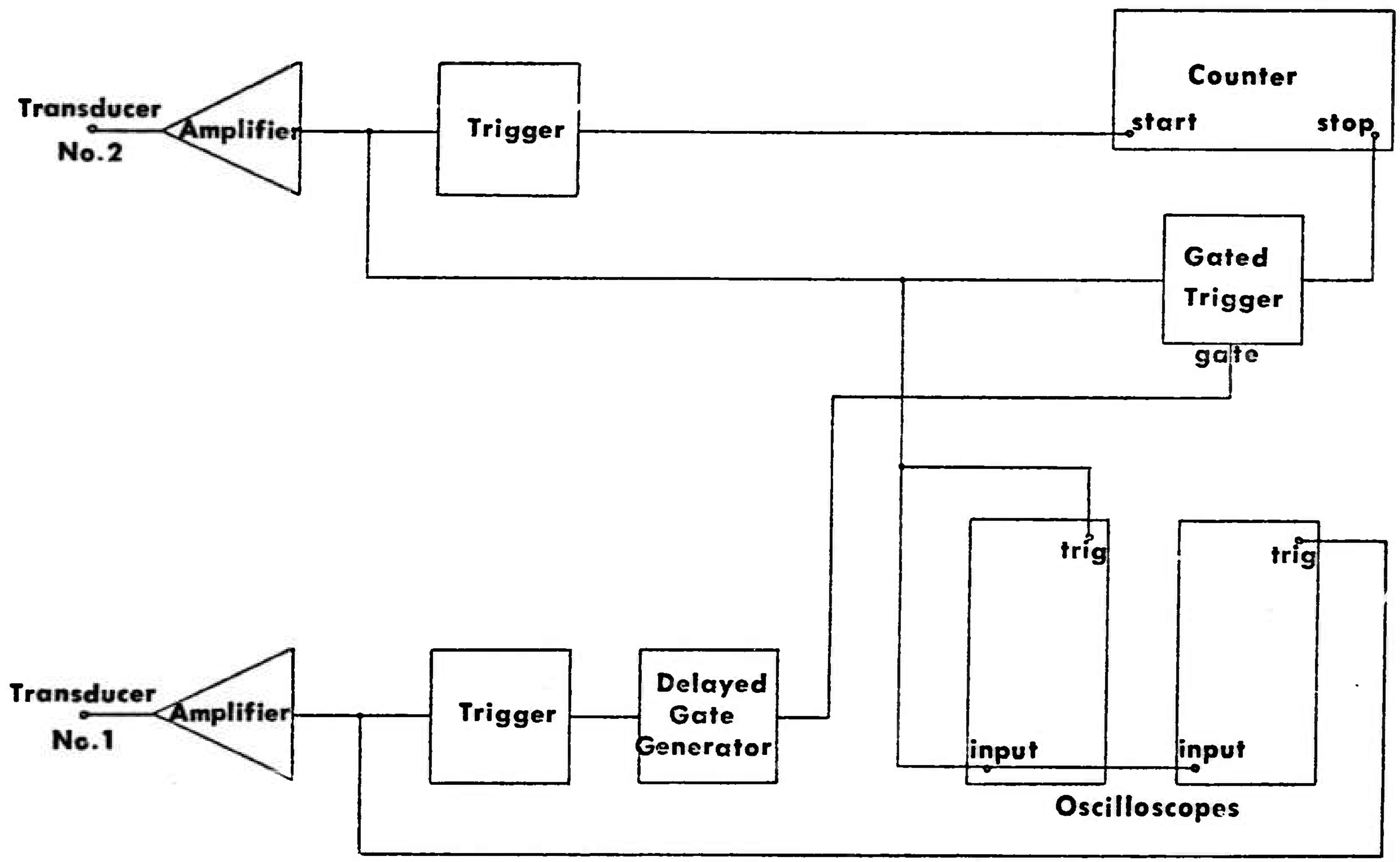

FIGURE 6. - Block diagram of circuitry used in underwater facility.

which is proportional to the bubble volume at any given pressure, is proportional to the cube of the bubble period. These two measurements, the square of the transducer output integrated over the time, and the cube of the bubble period may be normalized by the corresponding measurements for an equal weight of TNT to give "relative shock energy and relative bubble energy". The reproducibility of the "shock energy" determination is good (ca 5 percent) and that of the "bubble energy" is remarkable (less than 1 percent).

4.6 Bichel Gage Test

An important property of explosives intended for underground use is the quantity of toxic fumes generated, in particular carbon monoxide, nitric oxide and nitrogen dioxide, which have threshold limit values (TLV's) of 50, 25 and 5 ppm respectively.

The quantity of toxic fumes generated by an explosive is measured by the Bichel gage (14) which is a heavy steel chamber which can be evacuated and in which a 200-gram charge of explosive may be detonated (unconfined). The pressure in the chamber following detonation is allowed to come to equilibrium and measured, permitting the calculation of the total quantity of gas generated, and a sample is taken for analysis of toxic constituents by gas chromatography.

4.7 Crawshaw-Jones Apparatus

Because the quantity of oxides of nitrogen depends on the conditions under which the explosive is detonated, especially the confinement, the Bichel gage is not adequate for determining the oxides of nitrogen in detonation products (2). To obtain a realistic estimate of the oxides of nitrogen under actual conditions of use, the Crawshaw-Jones apparatus is

used. This apparatus consists of a 90-liter cylindrical chamber, 17.5 cm in diameter and 3 meters long, which can be evacuated, and to which can be coupled a heavy-walled steel cannon with a 2-inch diameter bore-hole capable of holding 300 grams of explosive and one pound of fireclay stemming. The chamber is evacuated, the charge is fired, the temperature and pressure recorded after equilibration, and a sample of gas is taken and analyzed as for the Bichel gage.

5. Explosive Selection

5.1 Types Considered

A variety of different explosive systems were considered for possible use in the continuous explosive fragmentation program. Among the types examined were commercial dynamites, a number of different brands of commercial ammonium nitrate-fuel oil (ANFO), and other two-component explosive systems, as well as a variety of commercial and experimental water gels. These different explosive systems are described briefly.

The most common commercial high explosives used in the United States are compositions sensitized with nitroglycerin--the so-called dynamites. Nitrostarch is also used as a sensitizer. The chief components of straight nitroglycerin dynamite are nitroglycerin and sodium nitrate whose combined weight is roughly 80 percent of the total weight of the explosive. Straight dynamites also contain roughly 15 percent carbonaceous fuel, an antacid agent, and frequently a small percentage of sulfur. Ammonia dynamites have compositions similar to the straight dynamites except that ammonium nitrate is used to replace a portion of the nitroglycerin and sodium nitrate. A typical composition having inter-

mediate strength would contain 15 percent nitroglycerin, 40 percent sodium nitrate, 30 percent ammonium nitrate, 10 percent carbonaceous fuels, 4 percent sulfur, and 1 percent antacid. The dynamites can be initiated with a No. 6 or 8 blasting cap and are capable of detonating in relatively small diameters of the order of one inch.

Ammonium nitrate-fuel oil is the most widely used blasting agent in the world. It contains 94.5 percent ammonium nitrate and 5.5 percent fuel oil for an oxygen-balanced system. Ordinarily ANFO is not cap-sensitive and is very inefficient when used in small-diameter boreholes.

Another recent product line to appear on the commercial market is the so-called "<u>two-component explosives</u>". They resemble ANFO in that they consist of two separate components, neither of which is classified as an explosive, which when mixed together form a cap-sensitive explosive. They have the advantage over premixed explosives in that they can be shipped and stored without all of the restrictions applicable to explosives and blasting agents.

A <u>water-gel explosive</u> is an explosive which consists basically of one or more fuels, one or more oxidizers, and usually a sensitizer dispersed in a thickened or gelled aqueous medium.

In essence, all explosives may be thought of as falling into one of three categories: molecular explosives such as nitroglycerin in which the fuel and oxidizer are parts of the same molecule, heterogeneous explosives such as black powder which are a mixture of discrete substances which are either fuels or oxidizers, and homogeneous mixtures of fuel and oxidizer such as solutions of soluble fuels in nitric acid. However,

the definitions of "fuel", "oxidizer", and "explosive" all tend to be somewhat blurred since some "explosives", e.g., TNT, contain inadequate oxygen and may thus act as fuels in the presence of supplemental oxidizers, and some "oxidizers", e.g., ammonium nitrate (AN), contain enough fuel to function effectively as an explosive when adequate charge diameter, confinement and initiating stimulus exist. Thus, the earliest water-gel explosives which consisted largely of TNT and AN slurried in water may be thought of as attempts to supplement the oxygen content of the explosive TNT by adding AN, or to sensitize the explosive AN by adding the more sensitive TNT. This type of explosive, like any other, may incorporate aluminum to enhance the energy due to the high heat for formation of aluminum oxide.

6. Explosive Evaluation

In order to determine the advantages and disadvantages of the various explosive types available, representative samples from each of the above types were examined for energy release, sensitivity and toxic fume production. Test results obtained with four commercial dynamites, five experimental and two commercial water gels, two commercial ammonium nitrate-fuel oil mixes and two commercial two-component systems are summarized in table 1. As a basis of comparison, we chose the commercial dynamite designated D-1351 which is a "40% extra" dynamite, commonly used in hard-rock blasting.

6.1 Energy Considerations

For any given application of an explosive, an optimum value exists for the explosive shock and heaving energy. Criteria for a suitable

Table 1. - Summary of Results of Explosives Survey

Explosive Designation	Density (g/cc)	Detonation Velocity (m/sec)	Casing Velocity (m/sec)	Shock Energy	Bubble Energy	V_{50} (m/sec)	#6 Cap Sensitivity	Fume Class
Commercial Dynamites								
P-1312	1.12	3820	560	88.1	91.9	154	Yes	2
D-1316	1.68	4690	680	74.4	95.5	140	Yes	-
P-1308	1.34	5230	880	82.6	92.7	∿ 100	Yes	2
D-1351	1.75	5560	770	92.7	105	170	Yes	1
Experimental Water Gels								
PB-1	1.75	6040	1230	159	209	969	No	-
270-C	1.26	4300	660	90.0	123.8	384	Yes	1
270-H	1.45	4150	580	93.8	132.9	∿ 400	Yes	1
272-C	1.27	4370	660	94.8	128.6	264	Yes	1
272-H	1.34	4110	600	105.2	127.4	∿ 400	Yes	1
Commercial Water Gels								
P-1257	1.08	3290	440	46.0	69.2	336	Yes	2
P-1340	1.27	4860	790	74.6	94.2	410	Yes	1
Commercial AN-FO								
X-1247	0.89	2370	510	72.8	90.4	∿1000	No	1
X-1250	0.90	2510	480	74.6	87.5	900	No	1
Commercial 2-Component								
X-1334	1.38	5760	970	110	106	538	Yes	2
X-1406	1.38	8290	917	108.4	97.3	< 146	Yes	1

value of explosive energy are difficult to establish without considering the problems of a specific mining or tunneling operation. For example, many hard-rock operations such as taconite mining may find that ammonium nitrate-fuel oil produces inferior breakage. The data of table 1 show the two commercial ANFO mixes yield casing velocities of about 500 m/sec in the expanding cylinder test and relative shock and bubble energies of approximately 75 and 90 respectively, as determined in the underwater test. These values certainly represent the lower limits if the explosive is to be at all useful in the continuous fragmentation program; much higher values would be preferred. For example, the comparison dynamite D-1351 yielded values of 770 m/sec, 92.7 and 105 for casing velocity, shock and bubble energy respectively. These values probably represent a practical lower limit for the candidate explosives. Using values observed for D-1351 as acceptance criteria insofar as energy is concerned, we see that various commercial dynamites, experimental and commercial water gels and the commercial two-component systems have adequate energy for the problem at hand.

6.2 Sensitivity Considerations

In this application as well as in most others, there are two complementary aspects of explosive sensitivity: the explosive must be insensitive enough to be safe but sensitive enough to be initiated reliably by the chosen initiator system and detonate reliably in the charge size selected for application. There are a large number of tests for explosive sensitivity, including the drop-weight impact test, friction test, card-gap test, projectile impact test and electrostatic spark sensitivity

test. All of these tests should be run on an explosive before it is proposed for use. However, for preliminary screening purposes, the projectile impact test is adequate and experience with this test shows that this test is a reliable indicator of the hazards of explosives exposed to shock. Again, there are no absolute criteria for establishing limits of explosive sensitivity for the explosives considered in the continuous fragmentation program. From the safety viewpoint, it is believed that explosives having a V_{50} of the order of 100 m/sec would be too sensitive for the rigors envisioned in a continuous drill-blast application. On the other hand, the explosive cannot be too insensitive because of initiator requirements. While the exact initiation scheme has not been selected, a practical guideline would be that the explosive must be cap-sensitive. Past experience shows that the explosives having a V_{50} greater than approximately 850 m/sec are no longer cap-sensitive. With both safety and utility being considered, an explosive having a V_{50} between 200 and 600 m/sec would be suitable for the intended application. From the data in table 1, some of the experimental and commercial water gels and two-component systems meet this criterion.

6.3 Toxic Fume Considerations

There are no universal standards for the approval of explosives on the basis of their toxic fume production. The Bureau of Mines requires that total poisonous gases produced must not exceed 2.5 cu ft/lb of explosive for explosives used in underground coal mines where ventilation is ordinarily good (18). Many states require that explosives intended for underground use meet the requirements of Fume Class I as defined by

the Institute of Makers of Explosives (IME); an explosive must not produce more than 0.16 standard cubic feet of toxic gases per explosive cartridge (1-1/4 inches by 8 inches) to qualify for Fume Class I. As table 1 shows, each class of explosive has at least one representative meeting IME Fume Class I requirements. However, for the intended operation, this criterion may not be adequate. Conceivably, most of the 0.16 cubic feet of toxic gas could be nitric oxide. Some experimental explosives have ranged as high as 0.4 percent oxides of nitrogen and typically produce 16 cubic feet of total gaseous products per pound. If this were to happen, assuming oxidation of nitric oxide to nitrogen dioxide in ambient air, then in order to meet the established threshold limit values of 5 ppm, 60,000 cubic feet of ventilating air per pound of explosive would be required. Thus, the fume classes shown in table 1 are used for screening purposes only; matching the explosive to the total system requires much more detailed knowledge of the explosive consumption rate, tunnel geometry and other parameters. Although the ultimate technique is envisioned as fully automated, the requirement that some personnel be present (for maintenance, etc.) would impose severe ventilation requirements as recognized by Peterson (16).

6.4 Other Considerations

Commercial explosives for use in hard rock in general should be only semi-rigid so that they can be tamped into the hole to optimize the coupling of the shock into the rock and to minimize voids which might hinder the propagation of detonation or lessen the bulk density. In particular, for automated loading an injectable bulk explosive is desirable (free-

flowing granular, gel, paste or liquid), but granular explosives do not give good density; and for horizontal boreholes, the explosive must not be too free-flowing. Hence, "gels" are considered to be the best choice. Note that while the term "gel" has a precise technical meaning, it is used here to mean a substance which does not have the flow properties of a true liquid but which can be made to flow with the application of a little pressure. The ideal explosive from a safety standpoint would be a gel which could be mixed _in situ_ from nonexplosive ingredients.

Water gels have the additional advantage in that their energy and sensitivity can be tailored to meet rather specific requirements. In principle, energy enhancement of water-base systems can involve almost unlimited combinations of fuel and/or oxidizer additives. However, the great heat of combustion of aluminum (7500 cal/g) combined with its low cost, and the fact that only a few oxidizing materials (nitrate and perchlorate salts) have acceptable stability, limits the practical variety of formulations. Generally speaking, the substitution of sodium nitrate and sodium perchlorate for some of the ammonium nitrate raises the density and the oxygen balance, thus permitting the incorporation of more fuel (aluminum). Other alkali metal and alkaline earth perchlorates and nitrates (e.g., lithium, calcium) might be expected on the same basis to be even better; however, experience with calcium nitrate at the Pittsburgh Mining and Safety Research Center shows an adverse effect on both sensitivity and stability. Reasons for this behavior are not completely understood.

As indicated previously, the earliest water-gel or slurry explosive

contained TNT as a sensitizer. An interesting class of water gels contains no molecular explosive sensitizer; rather, powdered or flaked aluminum performs the sensitizing function. The exact mechanism of sensitization with aluminum is not known but it is almost certainly associated with "hot spot" formation.

In any water-gel explosive, these hot spots are probably air or gas bubbles. Although air bubbles are not observed directly, the existence of trapped air can be inferred from the low bulk density, ca 1.1 g/cm^3, compared with that of ca 1.4 g/cm^3 expected for a saturated solution of AN containing additional AN and aluminum in suspension, and also from the fact that water gels can be desensitized in some cases by applying pressure of a few atmospheres. This entrapped air need not be added intentionally; it apparently enters the mixture by way of the AN prills whose density is considerably less than the crystal density of AN and which must thus be presumed to contain appreciable air space. In attaining the required sensitivity and critical diameter then, the essence of the sensitization problem consists in providing enough bubbles at the fuel/oxidizer interface, assuming that the fuel and oxidizer themselves have sufficient reactivity. For aluminum-sensitized water gels, since the size and number of air bubbles are not readily controlled, the most important readily controllable parameters influencing sensitivity have been found to be the quantity, grain size, and type of aluminum. Extensive research at the Bureau over the past several years aimed at finding an economical sensitizing agent for water gels, and particularly at optimizing the aluminum from an economic point of view has shown very little promise for sensitizers other than aluminum except for molecular

explosives in the amount of 20 percent or more, although there have been reports in the literature of slurries sensitized with resin microballoons. Further research on the type and quantity of aluminum required for cap sensitivity has shown that fine-grained aluminum is not sufficient, but that flake (pigment grade) aluminum having a very high specific surface area is required, and most important that the aluminum particles have a hydrophobic coating such as stearic acid. The function of the hydrophobic coating may be twofold: First, it provides a surface on which the air bubbles can be trapped at a strategic location (the fuel/oxidizer interface), and second, the coating may possibly help protect the aluminum against attack by the aqueous medium. For example, if the aluminum grains have a hydrophobic coating, satisfactory sensitivity and critical diameter can be maintained with aluminum surface areas as small as 0.1 m^2 per gram of slurry.

Stability of water-gel explosives is another problem that must be considered if the explosives are to be stored for any length of time. The state of art of water-gel stabilization seems to be reasonably well-developed and serious problems in this area are not anticipated, especially since in-situ mixing of explosives is envisioned for the continuous drill-blast system.

7. Initiation Systems

Aside from considerations of the explosives per se, the prime difficulty in automating an explosives operation lies in the initiation system. Normally, explosive initiation is accomplished by electric or fuse-type blasting caps. The insertion and connection of a large number

of caps would be a complex process for an automated system to handle. Thus, a major portion of the research effort in this program was devoted to the selection and development of a remote initiation system compatible with the continuous drill and blast concept. The various methods explored will be discussed in this section of the report.

7.1 Mechanically Actuated Blasting Caps

These devices (also called "stab" detonators) are essentially blasting caps which are actuated by the rapid insertion of a firing pin or by the rapid withdrawal of a friction pin. It is conceivable that they could be automatically inserted into a loaded borehole and actuated by a small projectile, eliminating the need for mechanical contact with the initiation system. This method has no distinct advantage over the direct initiation of the explosive by projectile impact (this will be discussed in some detail) and has the disadvantage of adding to the cost of the operation.

7.2 Thermally Actuated Blasting Caps

The most familiar representatives of this class are the conventional blasting caps which are intended to be ignited by safety fuse, the so-called fuse caps. Although the connection and ignition of safety fuse (or of detonating cord if it is desired to transfer detonation to the boreholes in this way) presents as great a problem as that of wiring electric blasting caps, it is conceivable that the conventional blasting cap could be initiated in other ways. Possible techniques for this would include spraying the blasting cap with hypergolic liquids (see section 7.6) or filling the vicinity of the face with a flammable gas mixture

which, when ignited by a spark, would in turn initiate the cap.

7.3 Laser Ignition of Fuse Caps

If the economics of the overall excavation process are such that blasting caps would be used, then one attractive possibility for remote initiation would be the initiation of a fuse cap by a laser beam. To further explore this possibility, a series of experiments were conducted using the scheme indicated in fig. 7. For these tests, a focused or unfocused laser beam was directed at the active element of a conventional fuse cap placed in an explosion chamber. A Holobeam[3/], Series 300, system was used. It contains a water-cooled ruby rod laser which can deliver a maximum of 10 joules in a nominal 1.0-msec pulse at a wavelength of 6943Å. The beam divergence is 3 to 5 milliradians with a beam diameter of approximately 1.0 cm. The line width at 6943Å is less than 0.1Å.

Laser beam energy incident on the active element of the blasting cap was determined using a Quontronix Corporation, Series 500, Laser Energy/Power Meter which is essentially a ballistic thermopile. Trials were conducted with both an unfocused laser beam and beams focused by an auxiliary lens to increase the energy density. In all cases, the beam was projected through a 1/8-inch thick plexiglas protective port which reduced total available beam energy from 10 joules to 7.85 joules. When necessary, further beam energy reduction was accomplished by inserting semi-opaque filters in the beam path.

In all, three fuse-cap types from different manufacturers were tested to determine laser beam energy required for initiation. The sen-

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3/ Reference to trade names is made for identification only and does not imply endorsement by the Bureau of Mines.

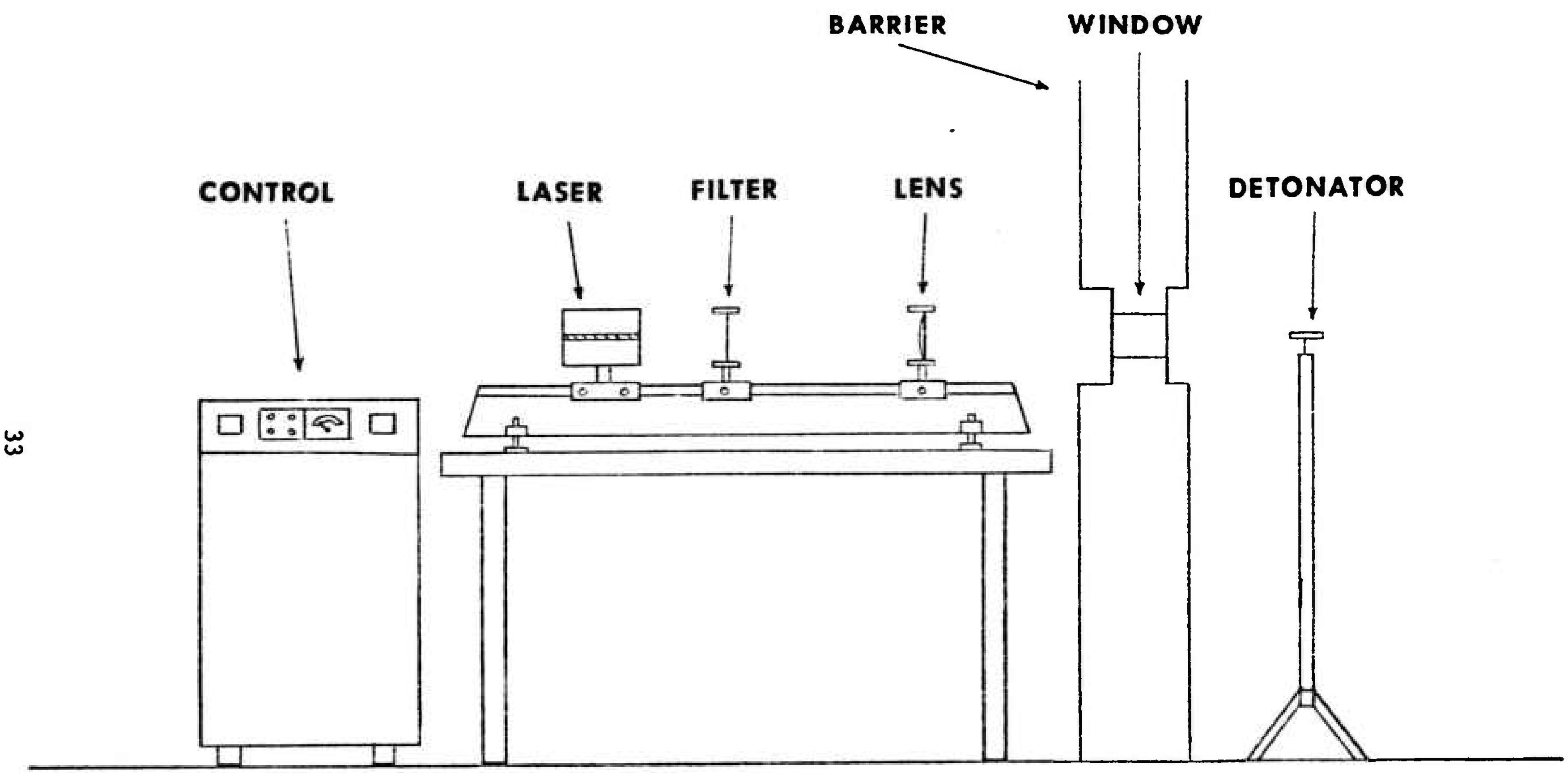

FIGURE 7. - Apparatus used in laser ignition studies.

sitivity of the caps was observed to vary widely. One type of cap would be initiated with a laser beam energy density of 0.019 joules/cm^2 which is well within the capability of the unfocused laser beam. A second cap type required focusing the incident beam down to a 0.08-cm diameter in order to increase energy density to 380 joules/cm^2 before initiation could be accomplished. A third fuse-cap type exhibited erratic response but could be initiated with a beam energy density of .035 joules/cm^2.

The important conclusion from this series of tests is that fuse caps are available that can easily be initiated with lens power unfocused laser beams. One can therefore envision a remote initiation system where fuse caps, possibly containing a cheap plastic focusing lens, are automatically inserted into the borehole and initiated in exact sequence by a laser beam. This method is certainly attractive from the viewpoint of completely automating the entire drill-load-blast sequence.

7.4 Electric Blasting Caps

As already pointed out, the wiring of conventional electric blasting caps (EBC's) presents a complexity which would be desirable to avoid. There are, however, alternative ways of applying the electric energy without using wires which can be roughly classified as electrostatic, magnetic and radio frequency. In this connection, it should be pointed out that all of the alternative modes of initiation considered here initiate the charge at the outer end of the hole rather than the bottom of the hole. This is not a serious drawback for while there are some advantages (7) to placing the initiator at the back of the hole none of these is compelling. The same statements can be made regarding the

omission of stemming. In the electrostatic approach, the EBC is capacitively coupled to an electrode attached to a source of high potential which can be rapidly varied. The energy input to the cap in joules is given by

$$E = RC^2 \int \left(\frac{dV^2}{dt} \right) dt \qquad (1)$$

where R is the bridgewire resistance (ohms), C the coupling capacity (picofarads), $\frac{dV}{dt}$ the rate of change of the "transmitter" electrode potential in megavolts/microsecond, and t the time in seconds. If it is assumed that the voltage discharge is an underdamped oscillatory one with period ω (megahertz) and decay constant γ (seconds), the above becomes

$$E = \frac{RC^2V^2\omega^2}{4\gamma} \quad . \qquad (2)$$

In the magnetic approach, the EBC terminals would be connected to an integral, small wire loop which would be inductively coupled to a transmitter coil attached to a source of rapidly varying current. The energy output to the cap is given by

$$E = \frac{M^2}{R} \int \left(\frac{di}{dt} \right)^2 \qquad (3)$$

where M is the mutual inductance in microhenries, and $\frac{di}{dt}$ is the rate of change of current in the "transmitter" coil in amperes/microsecond. Making the assumption that the current varies with amplitude i and frequency ω and decay constant γ as above, this becomes

$$E = \frac{M^2 i^2 \omega^2}{4R\gamma} \quad . \qquad (4)$$

In the radio-frequency (RF) approach, the EBC is connected to a small

integral antenna; the electrical energy is transmitted from anotner antenna connected to a pulsed power source. If G is the gain of the "transmitter" antenna, A is the effective area of the receiver antenna (in cm^2), P is the RF power radiated (in watts), τ is the pulse duration (in seconds), assuming a square wave, and r is the separation (in cm) between transmitter and receiver, assuming that the wavelength $\lambda >> \sqrt{A} >> \gamma$

$$E = \frac{GAP}{4\pi r^2} \quad . \tag{5}$$

No experiments were performed to evaluate the above concepts; however, the substitution of "reasonable" values into the above equations shows that any of the above is feasible using available equipment and EBC's. However, the expense entailed by the use of these "special" EBC's might be prohibitive.

7.5 Gaseous Detonation

In principle, it is possible to initiate detonation in a solid or liquid explosive by the impingement of a detonation in an adjacent gaseous medium; however, extensive research on this phenomenon by other investigators at the Bureau of Mines (13, 14) appears to show that initial pressures (in the gaseous medium) of at least a few tens of atmospheres are required and it is not obvious how this can be achieved simply in actual practice.

7.6 Deflagration-to-Detonation Transition (DDT) - Laser Initiated

The transition from deflagration to detonation of solid explosives is a well known (1) phenomenon. Since it was thought to be relatively easy to merely ignite explosives remotely, it was thought possible to

use this effect as a remote method of initiating detonation. Accordingly, several explosives whose properties seemed suitable for the application were evaluated regarding their tendency to DDT.

The apparatus used is shown in fig. 8. It consists of a 16-inch length of 1-inch Schedule 40 steel pipe capped at both ends with a vent hole in the initiation end and filled with the explosive to within 2 inches of this end. Into the vented end are inserted an electric matchhead and 10 grams of propellant powder to aid ignition. Experience with this system was disappointing in that no commercial type explosive except conventional dynamites would undergo DDT at all--even these would detonate only when a very "hot" ignition was used (an aluminum/ammonium perchlorate-base propellant) and even then only when the vent in the end of the simulated borehole was constricted to half the cross-sectional area of the borehole itself. In addition, it was found to be not as easy as originally thought to ignite explosives or propellants with a small pulsed laser; with the laser available, capable of delivering 10 joules in a few hundred microseconds, only metallic sulfide/chlorate compositions were readily and reliably ignitable.

It should be pointed out these results do not negate the feasibility of this approach; it is quite conceivable that, with a more intense ignition source (laser), this method could be made practical.

7.7 DDT - Hypergolic Initiation

Two substances are called hypergolic (with respect to one another) if they react on contact with sufficient intensity to produce ignition. Such ignitions can be violent and it was that that DDT could be produced

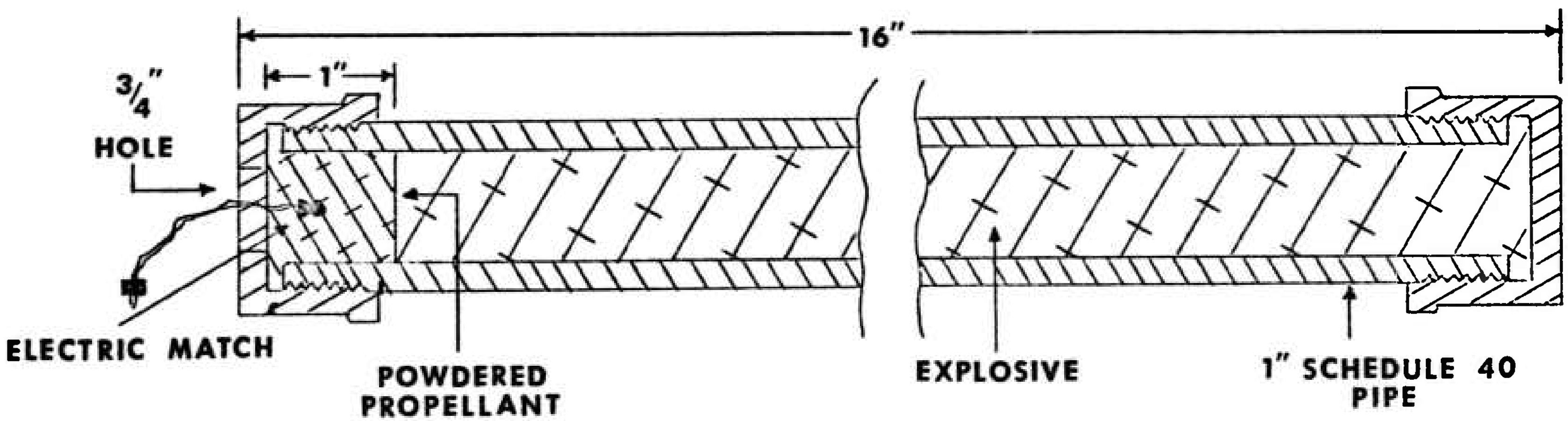

FIGURE 8. - Apparatus used in deflagration-to-detonation transition studies.

in this way with the additional advantage that the initiation is accomplished merely by injecting a stream of a liquid which is hypergolic with the explosive in the borehole (or injecting two hypergolic liquids simultaneously). Considerable experimentation with this idea was done using the same apparatus that was used in the experiments described in paragraph 7.5, except that the electric matchhead and propellant are replaced by the ends of two pieces of tubing through which opposing jets of hypergolic liquids are driven by applying compressed air to the liquid reservoirs (in some experiments a single stream of liquid was directed at a second substance already in the "borehole"). The quantity of hypergolic material was arbitrarily fixed at 10 grams.

The system initially tried was a anhydrous hydrazine and red fuming nitric acid (RFNA), 20% NO_2, which is well known from rocket propellant work to be violently hypergolic and a gelatin dynamite containing a high proportion of nitroglycerin. Results obtained with this system were even more disappointing than those with the powdered propellant and electric matchhead; DDT's were obtained only when the cross-sectional area of the vent hole at the initiation end was of the order of 0.015 times that of the "borehole". Accordingly, several modifications of this system were tried, including catalysts for the hydrazine-RFNA system in the form of transition metal compounds, e.g., ferric chloride, sodium nitroprusside, dissolved in the respective liquids but without success. This system was further modified by replacing the RFNA by perchloric acid (70%) and/or replacing the hydrazine with substituted hydrazines (mono- and dimethyl), also without improvement. A slightly different approach was taken by

mixing a fuel with a salt of an unstable oxidizing acid, e.g., chloric, permanganic, inserting this into the "borehole" and injecting sulfuric acid to liberate the oxidizing acid. Considerable improvement was obtained with this system, especially using a mixture of powdered aluminum, potassium chlorate, and PETN in contact with the explosive. DDT's were obtained with vent hole diameters as large as a one-quarter of the cross-sectional area of the borehole. Even this is not adequate however, and considering the hazardous nature of the substances which need to be handled, this approach was evaluated as being a possibility but not as a promising candidate.

7.8 Direct Laser Initiation

Direct laser initiation of high explosives is possible using a Q-switched ruby laser pulse as has been reported in the literature (21). No attempt was made to further evaluate this method which remains a distinct possibility. However, high laser energy requirements might lead to prohibitive costs.

7.9 Projectile Impact Initiation

The direct initiation of high explosives by projectile impact is a well-established fact and projectile impact serves as one basis for classifying the relative sensitivities of explosives. For the intended application, projectile impact initiation appears very attractive from both the economic and practical viewpoints. The economic attractiveness would be enhanced if the explosive selected for use could be initiated with cheap, commercially available ammunition. While the 50-percent velocities as determined by the Bureau projectile impact test were known for

most of the explosive types considered, knowledge of the initiating capability of various types of commercial ammunition was lacking. For this reason, impact initiation trials were conducted on a number of explosives using a variety of commercial ammunition. The V_{50}'s of the explosives selected for these experiments were sufficiently different to permit a rough correlation between the observed V_{50} and the effectiveness of a particular type of ammunition in initiating the explosives.

The results of these experiments are presented in table 2 for three military explosives and a typical water gel and a gelatinous dynamite having V_{50}'s ranging from 170 to 790 m/sec. On examining the results, it is immediately obvious that none of the ammunition is capable of initiating an explosive if the V_{50} for that explosive is above approximately 450 m/sec. Progressively lower velocity ammunition becomes effective as the V_{50} is decreased and all but one of the commercial types were capable of initiating the gelled dynamite having a V_{50} of 170 m/sec. The water gel which was typical of the type considered for potential use in this program required high-velocity (more expensive) ammunition for initiation. In any case both dynamite and water gels can be initiated with conventional ammunition costing a few cents a round. However, even if the explosive selected did fall beyond the range of commercial ammunition, it should be possible to design a gas-driven gun capable of initiating the explosive with cheap expendable projectiles. All things considered, the remote initiation of explosives by projectile impact appears at present to be the safest, most attractive method for immediate application to the continuous drill-blast concept.

Table 2. - Results of Bullet Impact Tests on Selected Explosives

Ammunition					Explosive				
Name	Calibre	Bullet weight (grains)	Muzzle velocity (m/sec)	Type 1/	Composition B	50/50 pentolite	Tetryl	Water gel	Gel dynamite
300 Weatherby	.30	110	1150	JSP	N 2/	N	M	Y	Y
300 Weatherby	.30	220	885	JSR	-	N	N	N	Y
220 Swift	.22	48	1250	JSP	N	N	N	Y	Y
22 Hornet	.22	45	820	JSP	-	-	N	N	Y
22 Long Rifle HS	.22	40	407	UR	-	-	N	N	Y
22 Short HS	.22	29	340	UR	-	-	-	-	Y
22 Long Rifle	.22	40	350	UR	-	-	-	-	Y
22 Short	.22	29	320	UR	-	-	-	-	N
	V_{50} 3/ (m/sec)				790	440	415	435	170

1/ J = jacketed; U = unjacketed; S = soft point; P = pointed; R = rounded nose.

2/ N = no initiations; Y = initiated every time; M = mixed results.

3/ Velocity corresponding to 50% probability of initiation by .50-inch x .50-inch-cylindrical brass projectiles.

8. Conclusions and Recommendations

A variety of commercial and experimental explosives were examined for potential application in a continuous explosive tunneling program; emphasis was placed on measurements of energy release, toxic fume production and sensitivity. A "40 percent extra" dynamite commonly used in hard-rock blasting served as a basis of comparison. Data from this control explosive were used to establish acceptable limits of performance and toxic fume production; upper and lower sensitivity limits were dictated by safety considerations and compatibility with envisioned remote initiation systems.

None of the explosives tested was ideal in all respects. Adequate energy can be obtained from commercial dynamites, experimental and commercial water gels, and conventional two-component explosives but not from straight ANFO. From the viewpoint of toxic fume production, the explosive selected for use should at least meet the requirements of IME Fume Class 1, producing less than 0.16 cubic feet of poisonous gas per (1-1/4 inches by 8 inches) cartridge of explosive. The majority of the explosives tested fell into this category. In order to be compatible with many of the remote initiation systems considered, the explosive should be cap-sensitive or, in more quantitative terms, should have a V_{50} below 500 m/sec; a critical diameter of the order of 1.0 inch is implicit in this requirement. Dynamites, water gels and the two-component explosives meet this sensitivity requirement. However, it is felt that from the standpoint of safety, the lower limit or V_{50} should be about 200 m/sec, considering the rugged environment the explosive will be exposed to in application. Present dynamites in general would be elimi-

nated from consideration if this limit is adhered to. With all of these restrictions in mind, currently available water gels and certain two-component explosive systems appear to more nearly meet the requirements. However, it appears that all of the types of commercial explosives examined have sufficient flexibility in formulation and properties that an explosive from any of the groups considered could be tailored to the proposed application without difficulty.

A variety of different remote initiation systems were considered in principle and some of the more attractive ones were experimentally examined. Initiation by projectile impact appears to offer the best combination of simplicity, reliability and cost among all of the methods considered for remote initiation. Laser ignition of fuse caps inserted into the borehole was demonstrated to be feasible with currently available caps. This method would be very versatile and should be given further consideration. Either one of these methods could be applied to a continuous explosive tunneling technique with little additional research.

Future research in this area should concentrate on the development of an injectable explosive which can be mixed in situ from nonexplosive ingredients and used with commercially available injection systems. The more practical aspects of remote initiation by projectile impact or laser-initiated fuse caps should also be explored. It appears that there are no real technological road blocks in the design, construction and application of a practical continuous explosive tunneler.

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